TITLE: Tactile Displays in Virtual Environments

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Summary

Virtual Reality (VR) technology allows the user to perceive and experience sensory contact with a non-physical world. A complete Virtual Environment (VE) will provide this contact in all sensory modalities. However, even state-off-the-art VEs are often restricted to the visual modality only. The use of the tactile modality might not only result in an increased immersion, but may also enhance performance. An example that will be discussed in this paper is the use of the tactile channel to support the processing of degraded visual information. The lack of a wide visual field of view in VEs excludes the use of peripheral vision and may therefore degrade navigation, orientation, motion perception, and object detection. However, tactile actuators applied to the torso have a 360° horizontal 'field of touch', and may be suited to present navigation information.

1. Introduction

Developments in VR technology have mainly focussed on the visual sense. In the last decade, enormous improvements have been made regarding the speed and resolution of the image generators. However, the human senses are not restricted to the visual modality. Using the auditive and tactile modality as well in a VE might have several advantages. This paper will more specifically discuss the tactile sense in relation to VE use. I will restrict the tactile channel to 'the skin as information channel'. Thus, I will not include receptors in muscles and joints as part of the tactile sense. When these are included, one usually uses the term haptics. On the other hand, tactile information is not restricted to 'touching' (i.e., feeling objects), but also comprises (passive) vibro-tactile stimulation of the skin and temperature perception.

Employing the tactile modality has several potentially useful applications and advantages in VE, including the following:

1. The quality of the VE and user performance is likely to improve if the information that is available to the tactile sense in real life is present in the VE as well. This is certainly true for information that is predominantly perceived with the tactile channel, such as roughness of objects, and small vibrations.
2. Employing the tactile sense will enlarge the immersion of the observer in the VE. The VE is more complete, and sensory information may become congruent: I can feel what I see.
3. Tactile information can guide movements. An example is the potential role of tactile information in grasping. Users may have trouble in estimating the distance between their (virtual) hand and the object they want to grasp. Presenting a tactile gradient (i.e. a tactile intensity or frequency field around the object) which guides the user to the object and indicates the Euclidian distance between the object and the user's hand might support the degraded visual information in VEs. After grasping the object, tactile information may be used to indicate how much force must be applied to the object (see next point).
4. Tactile information can be a substitute for force feedback. Force feedback is essential for adequate user performance in interacting with virtual objects (e.g., instruments and weapons), but is also very difficult to present with contemporary VR technology. Tactile information as a substitution for force feedback has already proven its effectiveness in remote control situations.
5. The tactile sense may be helpful in overcoming the weak points that even state-of-the-art VE systems still have. For example, the field of view of the visuals is still reduced compared to real life; using the tactile sense to compensate for the lack of peripheral viewing is one of the possibilities.
6. Finally, the tactile modality may be used as a general information channel to present VE-related but not specific information, e.g., warning information.

For all these applications fundamental and applied knowledge is required for successful use in VEs, and moreover, for successful development of devices. At this moment, not all this knowledge is available or applicable. Areas that deserve attention include:

- body loci other than hand and fingers,
- sensory congruency (below, an example shows that this doesn't come naturally),
- cross-modal interaction,
- perceptual illusions,
- attention.

A simple experiment by Werkhoven and Van Erp (1998) showed that visual and tactile information is not always perceived consistently. They investigated the perception of open time intervals, either marked by visual stimuli (blinking squares on a monitor) or tactile stimuli (bursts

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of vibration on the fingertip. They compared standard intervals of 200 ms with uni- and cross-modal intervals, as is schematically presented in Figure 1 for the cross-modal condition.
The results of this experiment showed a large bias in the cross-modal condition: tactile time intervals are overestimated by 30% (see Figure 2). This indicates that sensory congruency is a non-trivial aspect of integrating sensory modalities in a VE.

Overview of the paper
This paper focuses on the use of the tactile modality to present navigation (i.e., direction) information. This application can help VE users in orientating in VEs, which may be difficult on the basis of restricted visual information only.
In the next section of the introduction, some examples of tactile displays are given. Chapter 2 describes some basic neurophysiology and psychophysical knowledge. An example of cataloguing spatio-temporal characteristics is given in chapter 3. Here, the spatial characteristics of the torso are described, including experimental data. This cataloguing is of primary interest for the application that is described in Chapter 4: using the torso to present tactile navigation information. The torso has three important advantages in this respect. First, it has a large surface, reducing the need to minimise actuator size or to keep the number of actuators low. Second, information presented to the torso does not interfere with actions performed with the hands, like controlling input devices. And third, the torso is a volume, and thus *a priori* interesting for presenting 2D or 3D information, like geographical or navigational information.

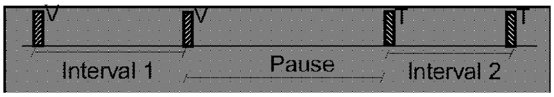

Figure 1: Schematic presentation of the stimuli to investigate the perception of open time intervals. The intervals are marked by visual stimuli (marked V) or tactile stimuli (marked T)

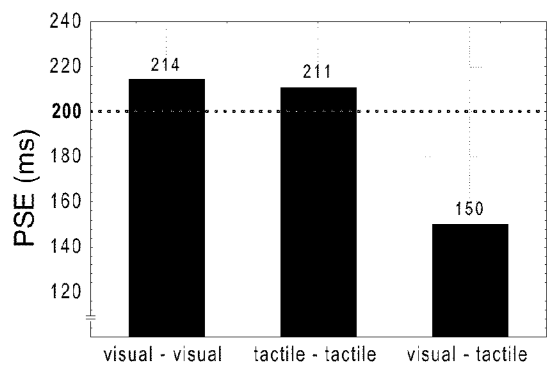

Figure 2: Point of subjective equality for a 200 ms standard open time interval experiment. The visual — tactile condition shows that a 150 ms tactile interval is judged to be equal in length to a 200 ms visual interval

Examples of tactile displays
This section gives a small and far from complete overview of tactile display applications (see also Van Erp & Van den Dobbelsteen, 1998). It focuses on two application areas: that of sensory substitution and navigation displays. This restriction is made, because displays developed for use in VE are regularly described in the open literature, e.g. see Boman (1995) or Ziegler (1996).

Sensory substitution
Some examples of the earliest displays providing complex stimuli are aids for the blind, including miniature matrices of point stimuli used for reading of text and pictures. 'Tactile imaging' is the process of turning a visual item, such as a picture, into a touchable version of the image, so that this tactile rendition faithfully represents the original information.

- *The Optacon.* One of the most successful devices to present 'visual' information to the blind was an ink-print reading machine, the Linvill-Bliss Optacon (OPtical-to-TActile CONverter). Bliss and his associates (Linvill & Bliss, 1966; Bliss et al., 1970) developed this reading device, which converts printed materials into vibratory patterns. With the aid of a small camera containing a matrix of 6 by 24 photocells, the device converts the image electronically to a tactile display, placed on the skin of a fingertip.
- *The Kinotact.* Craig (1974) studied letter-shape perception with the aid of a 10 by 10 matrix of vibrators placed against the observer's back. The encoding system, called 'Kinotact', was a 10 by 10 matrix of photocells, wired one-to-one with the vibrators. With the presentation of the tactile image of block letters, subjects learned to identify this 'pictorial mode' letter patterns to an average criterion of 80-90% correct in 300 trials. For related research, see also Loomis (1974), and Craig (1980).
- TVSS. Bach-Y-Rita (1972) and associates developed the Tactile Vision Substitution System (TVS system), in which a visual image picked up by a TV camera is transformed into a tactile one by means of a 20 by 20 matrix of vibrators mounted on the back of a dental chair. It was found that subjects could immediately recognise vertical, horizontal and diagonal lines. Experienced users could identify common objects and people's faces. This is an example of a perceptual phenomenon called distal attribution, in which an event is perceived as occurring at a location other than the physical stimulation site. With self-induced camera movement, subjects use the camera as part of a perceptual organ and learn to locate the percepts subjectively in space, rather than on the skin.

Another TVS system, called the Electrophthalm, developed by Starkiewicz, Kuprianowicz and Petruczenko (1971) is more applicable to space orientation and presents a 12 by 8 tactile image to the forehead. However, TVS systems are not useful for acquiring information from 'cluttered' visual environments and are not presently useful for navigation purposes.

- Desktop tactile displays. The formerly described systems are not designed to provide computer access to the visually impaired, and are rarely used due to uncomfortable or impractical displays and inefficient information transfer (Kaczmarek & Bach-Y-Rita, 1995). An example of a new generation display, which I will call desktop tactile displays, is the Moose. This display is especially designed to provide computer access. A prototype developed by O'Modhrain and Gillispie (1997) presents a haptic representation of a screen by reflecting forces when navigating across the screen. Desktop tactile displays are nowadays widely available in the consumer electronics shops for as little as 100 US$.

Tactile navigation displays

A second important application of tactile displays is as navigation display. Gilliland and Schlegel (1994) conducted studies to explore the use of vibrotactile stimulation of the human head to inform a pilot of possible threats or other situations in the flight environment. Rupert, Guedry and Rescke (1993) developed a matrix of vibro-tactors that covers the torso of the pilot's body (http://www.accel.namrl.navy.mil/default.html). This prototype may offer a means to continuously maintain spatial orientation by providing information about aircraft acceleration and direction of motion to the pilot. Within the pitch and roll limits of their torso display (15° and 45°, respectively), the subjects could position the simulated attitude of the aircraft by the tactile cues alone. The Tactor Evaluation System (TES, Engineering Acoustics Inc.) was developed to demonstrate the use of vibrotactile information for divers in conditions of low visibility: real time navigational information (course, distance, and cross-track error) and alarm information. Five tactors were used: left and right side, back and chest, and on a wrist for miscellaneous signals (http://www.eaiinfo.com/).

2. Cataloguing spatial sensitivity

An important parameter in the design and application of tactile displays is the spatial resolution. There are two main areas involved in spatial sensitivity research: neurophysiology and psychophysics. Important determinants of spatial sensitivity are the sizes and forms of the receptive fields of the mechanoreceptors, and the representation of the body surface in the (somatosensory) cortex. This neurophysiological data is presented in Section 2.1. The psychophysical measures of spatial sensitivity used throughout the years and experimental findings are presented in Section 2.2. For a more elaborate overview, see for example Van Erp and Vogels (1998). Basic research on the spatial sensitivity of the torso for vibro-tactile stimuli (relevant for the application under study) is presented in Chapter 3.

2.1 Neurophysiology

A comprehensive overview basic neurophysiology can be found in Kandel et al. (1991). An important contribution of this research area has been the determination of the density of receptors, and the size and form of the receptive field of a single peripheral nerve fibre. Micro-neurographic recordings from nerves innervating the glabrous skin have isolated four groups of mechanoreceptive fibres (see Table 1 for an overview).

After contacting a single afferent unit, a systematic exploration of the receptive field is undertaken. Unfortunately, this technique is only applied for the human arm and hand; no data on the trunk are available. Furthermore, the technique provides information on single peripheral nerve fibres only, not on the spatial sensitivity of the cutaneous sense as a whole. Applied to the Pacinian body, the receptive field proves to be large, with poorly defined borders and a single point of maximum sensitivity. Even for the fingers, receptive fields can be in the order of several square cm (Bolanowski et al., 1988; Valbo & Johansson, 1978).

Table 1: Characteristics of the four types of mechanoreceptive fibres in the human skin

	fast adapting	slowly adapting
superficial skin	**Meissner corpuscle (RA)** • small receptive field • NP I channel, not sensitive to temperature • 10–100 Hz • temporal summation: no • spatial summation: yes • local vibration and perception of localised movement	**Merkel cell (SAI)** • small receptive field • NP III channel, sensitive to temperature • 0.4–100 Hz • temporal summation: no • spatial summation: no • tactile form and roughness
deeper tissue	**Pacinian corpuscle (PC)** • large receptive field • P-channel, very sensitive to temperature • 40–800 Hz • temporal summation: yes • spatial summation: yes • perception of external events	**Ruffini ending (SAII)** • large receptive field • NP II channel, sensitive to temperature • 15–400 Hz • temporal summation: yes • spatial summation: ? • not in glaborous skin

Besides the receptive field sizes of single afferent nerve fibres, one has also determined the receptive field sizes of the different cortical regions involved in cutaneous processing.

2.2 Psychophysics

Within psychophysics, two classic measures are applied to determine the spatial resolving power: the two-point limen (participants have to judge whether a stimulus consists of one or two points) and the error of localisation (e.g. participants judge two successive contacts as the same or different in locus). Both methods know different variants. Unfortunately, little data are

available on vibro-tactile perception and on loci other than the hand.
Weber and Vierodt did the first psychophysical research on spatial acuity in the nineteenth century. It was Weber who introduced the two-point limen and the localisation error (Weber, 1834). Mapping of the whole body revealed large differences in spatial acuity between different parts of the body. Vierodt (1870) generalised this to the 'law of mobility', which states that the two-point limen improves with the mobility of the body part.

After the work of Weber and Vierodt, little attention was given to this field until the 1960s. Weinstein (1968) measured (pressure-) thresholds of two-point discrimination and tactile point localisation on several body loci. Both thresholds were highly correlated, however. Acuity found with two-point discrimination was three to four times lower than with point localisation. Because the methods of two-point discrimination and point localisation are measures for spatial acuity and hyper acuity, respectively, the results are in accordance with data on visual acuity (e.g. see Snippe, 1991). Furthermore, Weinstein found significant effects of body locus. Lowest thresholds were found for the fingertips: 2.5 mm and 1.5 mm for two-point discrimination and point localisation, respectively. Thresholds for the trunk were approximately 40 mm and 10 mm, respectively. Sensitivity decreased from distal to proximal regions: fingers, face, feet, trunk, upper and lower extremities. Thresholds correlated with the relative size of cortical areas subserving a body part. Another important observation was that good two-point discrimination did not necessarily mean good sensitivity to pressure. Vierck and Jones (1969; Jones and Vierck, 1973) stated that the method of the two-point limen leads to an under-estimation of the skin's real spatial sensitivity. They showed that the discrimination of area stimuli and length stimuli is about ten times better. In the 1970s, Loomis and Collins (1978) found comparable results when the stimulus was a gradual shift in the locus of stimulation.

Johnson and Phillips (1981) introduced alternative methods, and measured two-point thresholds, gap detection and discrimination of grating orientation for the fingertips. They found thresholds of 0.87 mm and 0.84 mm, respectively. These results show that the ability of subjects to discriminate stimuli is much finer than is indicated by the two-point threshold of Weinstein (1968).

3. Cataloguing vibro-tactile spatial resolution on the torso

Since only indirect data are available regarding the spatial resolution of the torso for vibro-tactile stimuli, basic research was needed to formulate the optimal display configuration. On the one hand, one wants to use the full information processing capacity that is available; on the other hand, one wants to keep the number of actuators to a minimum. Therefore, a concise discussion of a series of experiments is presented (for details, see Van Erp & Werkhoven, 1999).

Four male subjects (age range 28–39 years, mean 31) participated voluntarily. In the experiment, 11 vibro-tactile actuators were attached to the torso with sticky tape (see Figure 3). The participants performed a localisation task: Two stimuli were presented to the torso and the participant was asked to judge the location of the second compared to the first (left/right). The stimuli were first presented to the dorsal side of the torso, and in a second session to the frontal side. The inter stimulus interval (ISI) was varied (0 ms, 56 ms, 196 ms, and 980 ms), as was body locus within a torso side (left, middle, and right). The latter indicates the location of the standard stimulus; each standard was combined with four comparison stimuli. The responses of the subject to each standard-comparison pair were counted in proportion 'to the right' responses. These summarised data were fitted to a cumulative normal distribution, resulting in two parameters: μ (or bias) and σ (or threshold), see Figure 4.

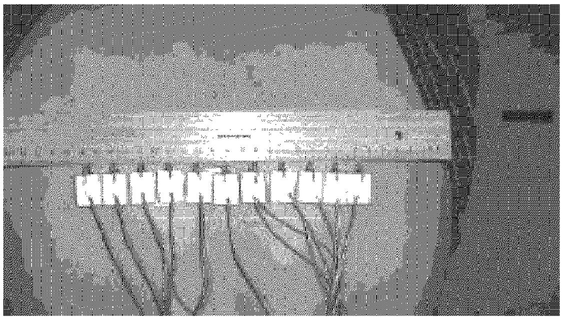

Figure 3: Placement of the tactile actuators on the back

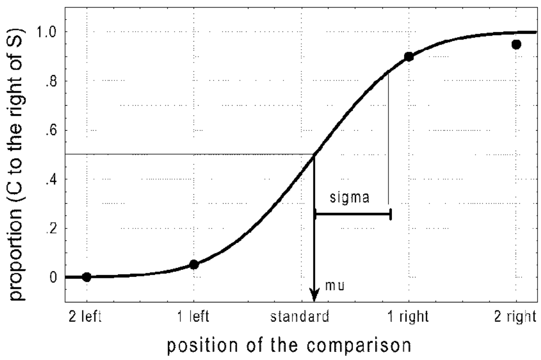

Figure 4: Psychophysical method to determine the bias (mu) and sensitivity (sigma) for a specific standard (S)

The results of the experiment (see Figure 5) showed that the sensitivity for vibro-tactile stimuli presented to the ventral part of the torso was larger than for stimuli presented to the dorsal part. Furthermore, the effect of body locus was present on both the frontal and the dorsal part: the sensitivity near the middle is larger than to the sides. Moreover, the sensitivity is larger than expected on the basis of the psychophysical literature. The effect of ISI showed that sensitivity increases with increasing ISI.

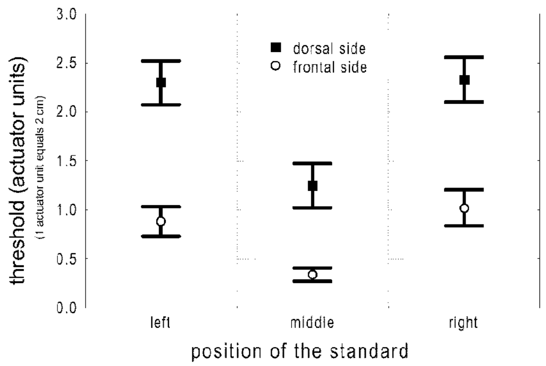

Figure 5: Results of the spatial accuracy of the torso for vibro-tactile stimuli

4. Example of implementing a tactile display: presentation of spatial information on the torso

When the first phase, cataloguing relevant perceptual characteristics, is finished, basic research into possible applications becomes actual. As discussed in the introduction, the torso may be well suited to present 2D geographical information. In the following experiment, tactile actuators were attached around the participants torso (except for the region around the spine, see also Figure 6). During the experiment, one actuator was activated. The observer could adjust a cursor to indicate the external direction suggested by the actuator (see Figure 7 for the experimental set-up).

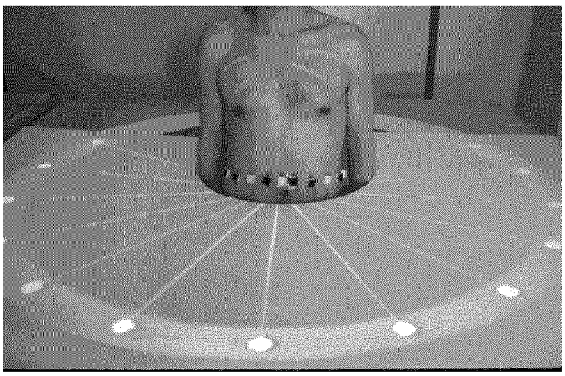

Figure 6: Method to ensure correct placement of the actuators

This direction determination task resulted in two parameters: a bias in the indicated direction, and variability in the answers (expressed in the standard deviation of the responses). The latter parameter is of course a measure of the precision with which the observer perceives the stimuli.

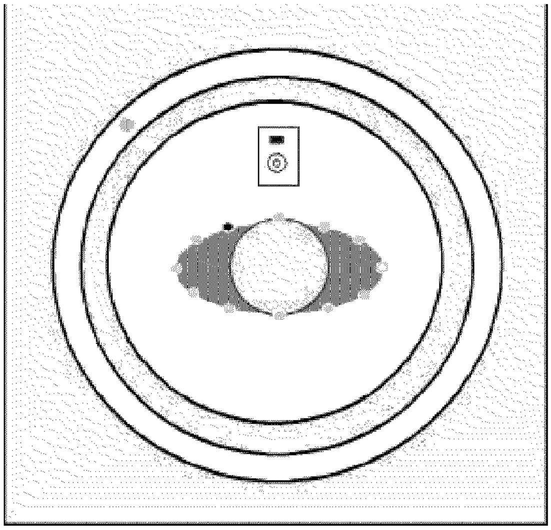

Figure 7: Top view of the set-up for the direction discrimination task. With a dial, the observer can position a cursor (a dot projected from above) along a white circle drawn on the table. The cursor should be positioned such that it indicates the direction of the tactile stimulus

The results are interesting in several ways. First of all, none of the participants had any trouble with the task. This is noteworthy since a point stimulus does not contain any explicit direction information. The strategy people use is probably equivalent to that of visual perception, namely using a perceptual ego-centre as second point. Several authors determined the visual ego-centre (e.g., Roelofs, 1959), which can be defined as the position in space at which a person experiences himself or herself to be. Identifying an ego-centre or internal reference point is important, because it co-ordinates physical space and phenomenal space. A second reason to determine the internal reference point in this tactile experiment was the striking bias all ten participants showed in their responses, namely a bias towards the sagittal plane. This means that stimuli on the frontal side of the torso were perceived as directions coming more from the navel, and stimuli on the dorsal side of the torso were perceived as coming more from the spine. Further research showed that this bias was not caused by the experimental set-up, the visual system, the subjective location of the stimuli, or other anomalies. The most probable explanation is the existence of two internal reference points: one for the left side of the torso, and one for the right side. When these internal reference points are determined as function of the body side stimulated, the left and right points are 6.2cm apart on average across the ten participants, see Figure 8.

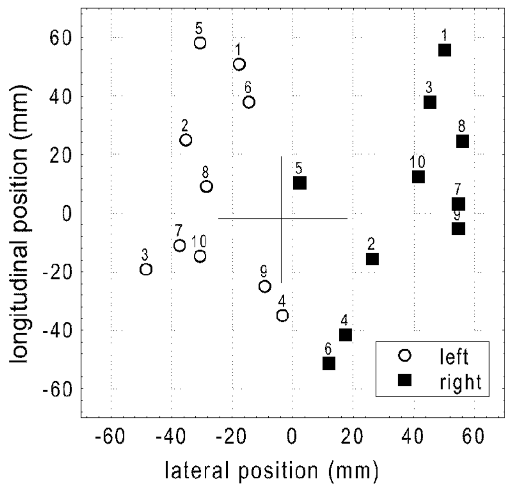

Figure 8: The Internal Reference Points for the ten observers in the tactile direction determination task

The third noteworthy observation is related to the variance of the responses as function of the presented direction. As Figure 9 shows (lower values indicate better performance), scores in the front-sagittal region (–50°—+50° in the graph) are very good with standard deviations between 4° and 8°, and somewhat lower towards the sides.

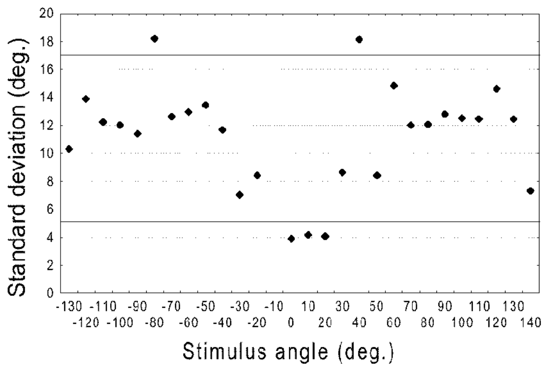

Figure 9: Standard Deviation of the tactile responses as function of the stimulus angle. The horizontal lines summarise the results of the post hoc test; pairs of data points significantly differ when separated by two lines

Other experiments and analysis with the same display are discussed more elaborately elsewhere (Van Erp, 2000). Relevant implications for the application of tactile displays for spatial information are the following:

- observers can perceive a single external tactile point stimulus as an indication of direction,
- although the consistency in the perceived direction varies with body location, performance near the sagittal plane (SD of 4°) is as good as with a comparable visual display,
- direction indication presented by the illusion of apparent location (the percept of one point stimuli located in between two simultaneously presented stimuli) is as good as that of real points,
- small changes in the perceived direction can be evoked by presenting one point stimulus to the frontal side, and one to the dorsal side of the observer.

5. Discussion

Potential beneficial areas of tactile displays in VE systems were presented in Chapter 1. After choosing what information the tactile display must be designed for to present, the relevant perceptual characteristics of the users must be determined. Although there is substantial literature on tactile perception, the available knowledge isn't by far as complete as on visual and auditive perception. Gaps in the required knowledge, e.g. on tactile perception of body loci other than the arms, hands, and fingers, must be filled before applications can be successful. Besides data on fundamental issues such as spatial and temporal resolution, perceptual illusions might be an interesting area in relation to display design. Illusions such as apparent position (which may double the spatial resolution of a display), and apparent motion (which allows to present the percept of a moving stimulus without moving the actuators) offer great opportunities to present information efficiently. Still more illusions are discovered (e.g., Cholewiak & Collins, 1999). After cataloguing all relevant basic knowledge, specific applications must be studied to further optimise information presentation and display use. Another important point, which is not fully addressed in this paper, is the interaction between the sensory modalities, and sensory congruency. An enhanced VE will be multi-modal, but the interaction between the tactile and the other senses is an area, which is only recently being addressed.

When these steps are taken carefully, tactile displays may enhance the experience and effectiveness of the VR.

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